Hydrologic and Hydrogeologic Information [40 CFR 146.82(a)(3)(vi), 146.82(a)(5)]

1 Lowermost Underground Source of Drinking Water

The primary regulatory focus of the USEPA injection well program is protection of human health and the environment, including protection of potential underground sources of drinking water (USDWs). The Underground Source of Drinking Water (USDW) is defined by the EPA as an aquifer which supplies any public water system and contains fewer than 10,000 mg/l total dissolved solids (TDS).

2 Determination of the Lowermost Base of The USDW

The most accurate method for determining formation fluid properties is through the analysis of formation fluid samples. In the absence of formation fluid sample analyses, data from open-hole geophysical well logs can be used to calculate formation fluid salinity by determining the resistivity of the formation fluid (R_w) and converting that resistivity value to salinity value. The two primary methods to derive formation fluid resistivity from geophysical logs are the "Spontaneous Potential Method" and the "Resistivity Method". The "Spontaneous Potential Method" derives the formation fluid resistivity from the resistivity of the mud filtrate, and the magnitude of the deflection of the spontaneous potential response (SP) of the formation (the electrical potential produced by the interaction of the formation water, the drilling fluid, and the shale content of the formations). The "Resistivity Method" determines formation fluid resistivity from the resistivity of the formation (R_t) and the formation resistivity factor (F), which is related to formation porosity and a cementation factor (Schlumberger, 1987).

2.1 Spontaneous Potential Method

The spontaneous potential curve on an open-hole geophysical well log records the electrical potential (voltage) produced by the interaction of the connate formation water, conductive drilling fluid, and certain ion selective rocks (shales). Opposite shale beds, the spontaneous potential curve usually defines a straight line (called the shale baseline), while opposite permeable formations, the spontaneous potential curve shows excursions (deflections) away from the shale baseline. The deflection may be to the left (negative) or to the right (positive), depending primarily on the relative salinities of the formation water and the drilling mud filtrate. When formation salinities are greater than the drilling mud filtrate salinity, the deflection is to the left. For the reverse salinity contrast, the deflection is to the right. When salinities of the formation fluid and the drilling mud filtrate are similar, no spontaneous potential deflection opposite a permeable bed will occur.

The deflection of the spontaneous potential curve away from the shale baseline in a clean sand is related to the equivalent resistivities of the formation water (r_{we}) and the drilling mud filtrate (r_{mf}) by the following formula:

$$SP = -K\ Log\left(\frac{r_{mf}}{r_{we}}\right) \qquad (1)$$

For NaCl solutions, K = 71 at 77°F and varies in direct proportion to temperature by the following relationship:

$$K = 61 + 0.133\ T° \qquad (2)$$

From the above equations, by knowing the formation temperature, the resistivity of the mud filtrate, and the spontaneous potential deflection away from the shale baseline, the resistivity of the formation water can be determined (Figure 2.1). From the formation water resistivity and the formation temperature, the salinity of the formation water can be calculated (Figure 2.2).

2.2 Resitivity Method

The Resistivity Method determines formation fluid resistivity from the resistivity of the formation (R_t) and the formation resistivity factor (F), which is related to formation porosity and a cementation factor (Schlumberger, 1987). The resistivity of a formation (R_t in ohm-meters) is a function of: 1) resistivity of the formation water, 2) amount and type of fluid present, and 3) the pore structure geometry. The rock matrix generally has zero conductivity (infinitely high resistivity) with the exception of some clay minerals, and therefore is not generally a factor in the resistivity log response. Induction geophysical logging determines resistivity or R_t by inducing electrical current into the formation and measuring conductivity (reciprocal of resistivity). The induction logging device investigates deeply into a formation and is focused to minimize the influences of borehole effects, surrounding formations, and invaded zone (Schlumberger, 1987). Therefore, the induction log measures the true resistivity of the formation (Schlumberger, 1987). The conductivity measured on the induction log is the most accurate resistivity measurement for resistivity under 2 ohm-meters.

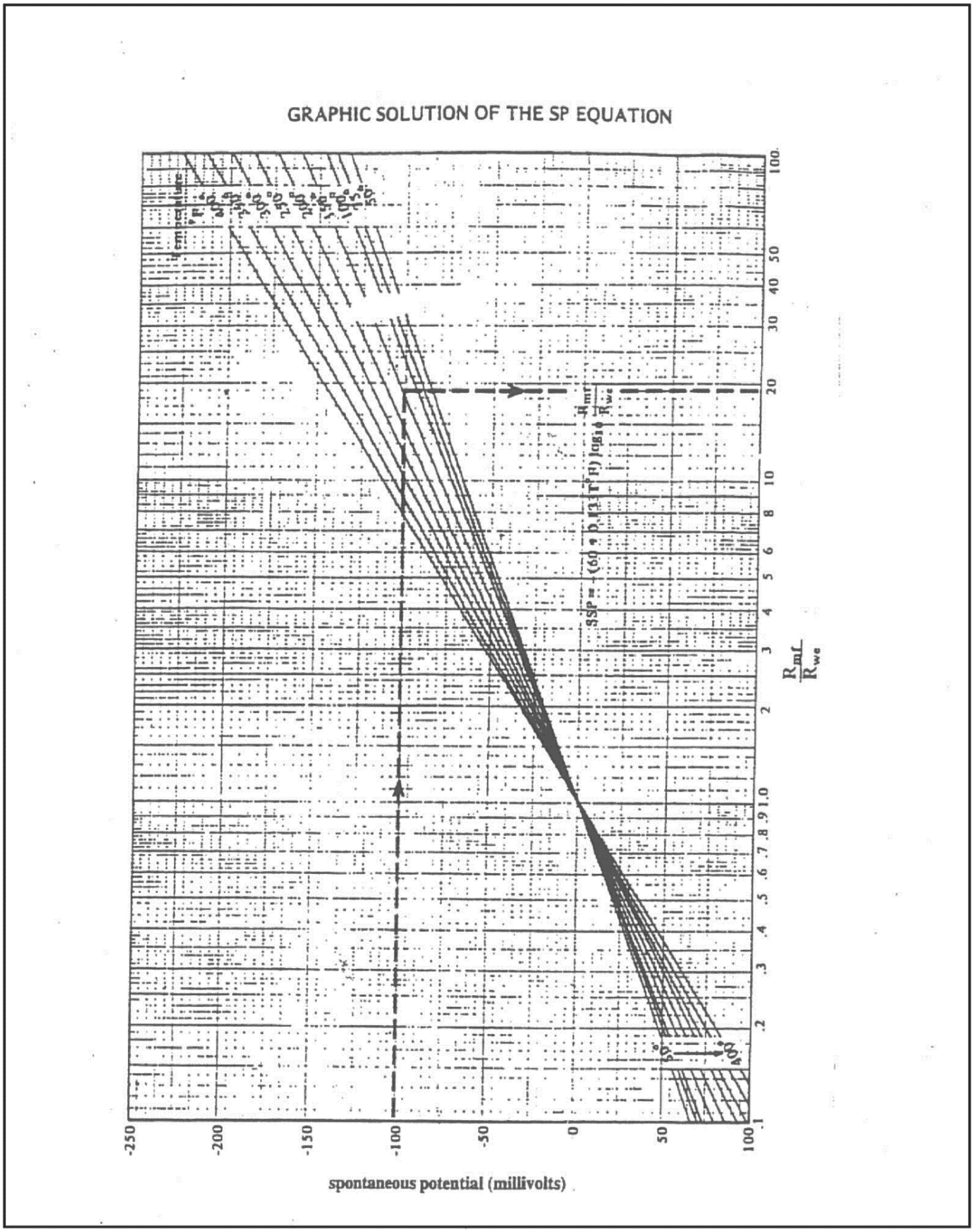

Figure 2.1 Graphic solution of the Spontaneous Potential Equation (Schlumberger, 1987)

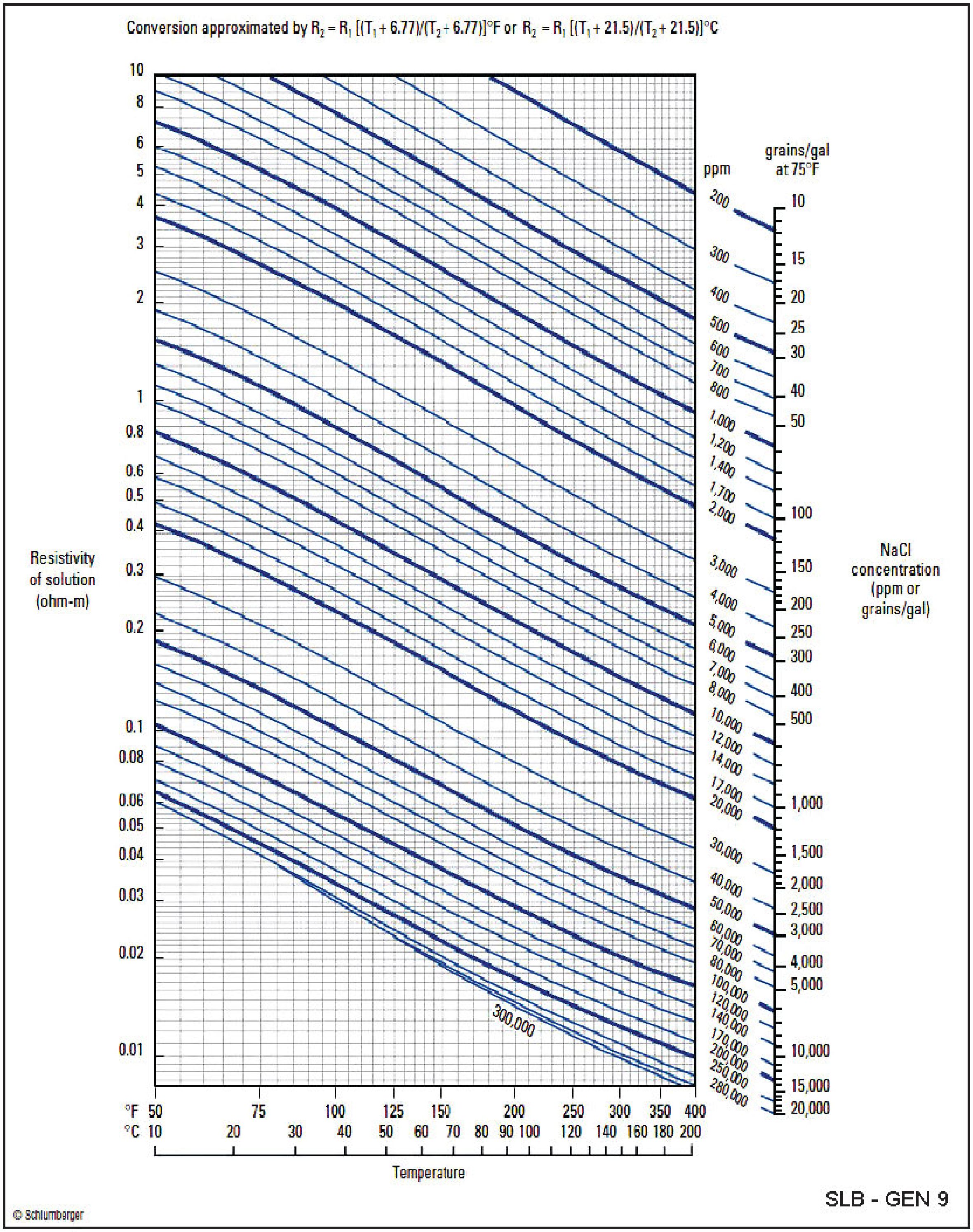

Figure 2.2 Resistivity nomograph for NaCl solutions (Schlumberger, 1979)

Electrical conduction in sedimentary rocks almost always results from the transport of ions in the pore-filled formation water and is affected by the amount and type of fluid present and pore structure geometry (Schlumberger, 1988).

In general, high-porosity sediments with open, well-connected pores have lower resistivity, and low-porosity sediments with sinuous and constricted pore systems have higher resistivity. It has been established experimentally that the resistivity of a clean, water-bearing formation (*i.e.,* one containing no appreciable clay or hydrocarbons) is proportional to the resistivity of the saline formation water (Schlumberger, 1988). The constant of proportionality for this relationship is called the formation resistivity factor (F), where:

$$F = \frac{R_t}{R_w} \tag{3}$$

For a given porosity, the formation resistivity factor (F) remains nearly constant for all values of R_w below 1.0 ohm-meter. For fresher, more resistive waters, the value of F may decrease as R_w increases (Schlumberger, 1987). It has been found that for a given formation water, the greater the porosity of a formation, the lower the resistivity of the formation (R_t) and the lower the formation factor. Therefore, the formation factor is inversely related to the formation porosity. In 1942, G.E Archie proposed the following relationship (commonly known as Archie's Law) between the formation factor and porosity based on experimental data:

$$F = \frac{a}{\phi^m} \tag{4}$$

Where:

ϕ = porosity

a = an empirical constant

m = a cementation factor or exponent.

In sandstones, the cementation factor is assumed to be 2, but can vary from 1.2 to 2.2 (Stolper, 1994). In the shallower sandstones, as sorting, cementation, and compaction decrease, the cementation factor can also decrease (Stolper, 1994).

Experience over the years has shown that the following form of Archie's Law generally holds for sands in the Gulf Coast and is known as the Humble Relationship (Schlumberger, 1987):

$$F = \frac{0.81}{\phi^2} \tag{5}$$

Combining the equations for the Humble relationship and the definition of the formation factor, the resistivity of the formation water (r_{we}) is related to the formation resistivity (rt) by the following:

$$R_t = \frac{R_{we}\ x\ 0.81}{\phi^2} \tag{6}$$

3 Methodology

To determine the formation water resistivity in a particular zone, the resistivity of the drilling mud filtrate (obtained from the log header) at the depth of the zone must first be determined. Resistivities of saline solutions vary as a function of NaCl concentration and temperature. The relationship between temperature, NaCl concentration, and resistivity are typically shown in the form of a nomograph for computational ease (Figure 2). From Figure 1, the resistivity of the drilling mud filtrate can be corrected to the temperature of the zone of interest. A shale baseline is next established on the spontaneous potential curve and the deflection away from the shale baseline measured. A chart containing the graphic solution of the spontaneous potential Equation (1) (Figure 1) gives the solution for the ratio between the resistivity of the mud filtrate and the formation water (R_{mf}/R_{we}) based on the measured spontaneous potential curve deflection. The resistivity of the formation water at formation temperature can be determined from the R_{mf}/R_{we} ratio and converted to the equivalent NaCl concentration from Figure 2. Once the base of the lowermost USDW is established, a formation resistivity (R_t) cut off on the deep induction log can be established using Equation (6). This formation resistivity cut-off is used to establish the base of the lowermost USDW at the Minerva Site.

By manipulating Figures 1 and 2, a formation water resistivity of 0.35 ohm-m corresponds to a salinity of 10,000 mg/l TDS. At a temperature of approximately 90 °F, a formation water resistivity value of 0.45 ohm-m corresponds to a salinity of 10,000 mg/l TDS. Deeper intervals with higher temperatures will have a higher resistivity cut off for analysis.

From this water resistivity value and an estimate of formation porosity, a formation resistivity (R_t) cut-off can be calculated. For the Project Minerva site, the USDW is project to be relatively shallow, thus a formation water resistivity of 0.35 ohm-m is used. Using an assumed formation porosity of 34 percent (shallow unconsolidated sands) and solving for the total formation resistivity, gives the following result:

From Equation (6), a formation resistivity (R_t) cut-off can be calculated if the approximate formation porosity is known. Therefore, solving Equation (6) gives the following result:

$$R_t = \frac{0.35\ ohm - m\ x\ 0.81}{0.34^2} = 2.45\ ohm - m$$

Therefore, it is conservatively calculated that the sands with a formation resistivity of greater than 2 ohm-m were considered to be USDWs. This site-specific calculation is in agreement with the Louisiana Department of Natural Resources (LaDNR) guidance located at *http://www.dnr.louisiana.gov/assets/OC/im_div/uic_workshop/2_USDW.pdf*, which indicates that the USDW should fall between:

Ground surface to 1,000 feet: 3 ohms or greater is considered USDW;

1,000 feet to 2,000 feet: 2 ½ ohms or greater is considered USDW; and

2,000 feet and deeper: 2 ohms or greater is considered USDW.

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5 Regional Hydrogeology

The regional aquifer system is called the Gulf Coast Aquifer system and stretches from Texas, across Louisiana, Mississippi, and Alabama, and includes the western most portion of Florida. Miocene and younger formations contain usable quality water (<3,000 milligrams per liter (mg/L) TDS) and potentially usable quality water (<10,000 mg/L TDS), which is defined as base of lowermost USDW within this system. These aquifer systems regionally crop out in bands parallel to the coast and consists of units that dip and thicken towards the southeast. Baker (1979) describes four major hydrogeologic units that comprise the Gulf Coast Aquifer System in the Texas and Louisiana region. In ascending order, the four units are:

- the Jasper aquifer;
- the Burkeville confining system;
- the Evangeline aquifer;
- and the Chicot aquifer.

The Burkeville confining system hydrologically separates the Evangeline aquifer from the underlying Jasper aquifer. However, the Chicot and Evangeline aquifers are thought to be hydrologically connected. A hydrogeologic stratigraphic column for southwestern Louisiana is contained in Figure 5.1. The following sections provide details on the regional expanse and parameters pertaining the hydrostratigraphy for the defined systems from deepest to shallowest intervals. A regional stratigraphic section (A-A') parallel to dip from Baker (1979) depicting the aquifers in the regional area of Southeast, Texas is contained in Figure 5.2.

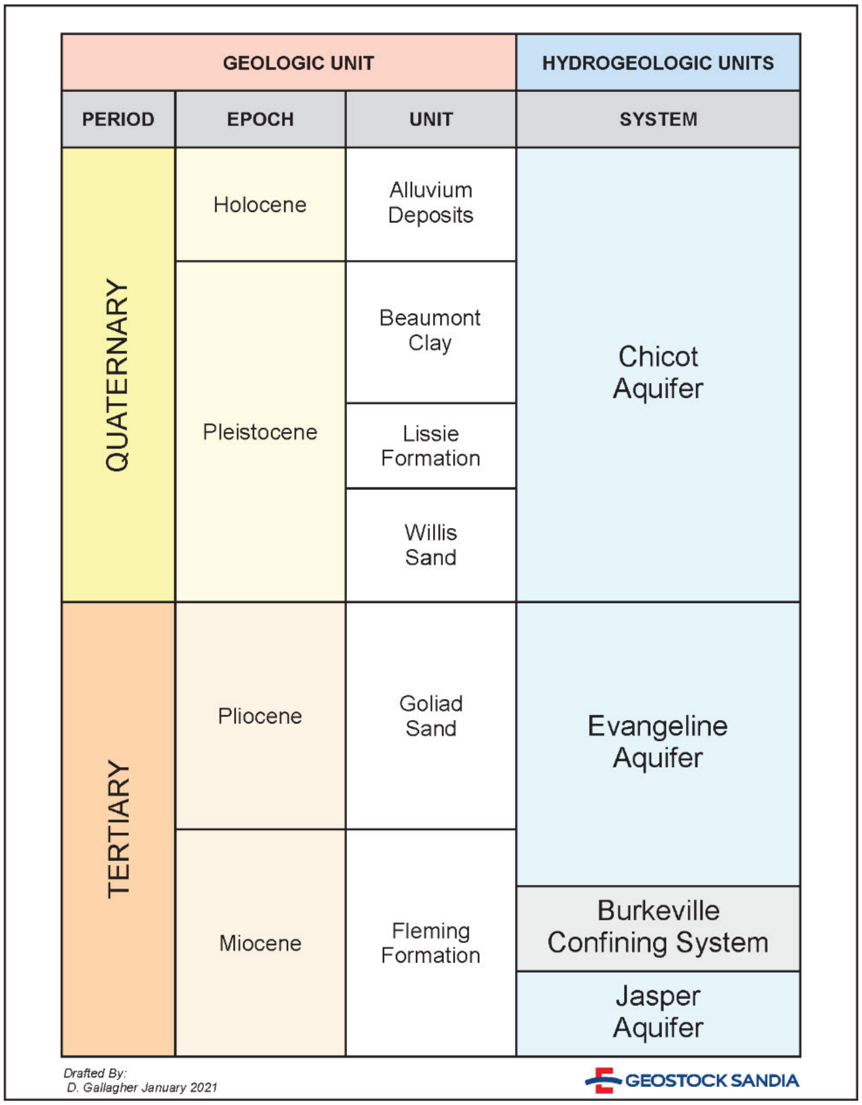

Figure 5.1 Regional hydrostratigraphic column for southeastern Texas and southwestern Louisiana.

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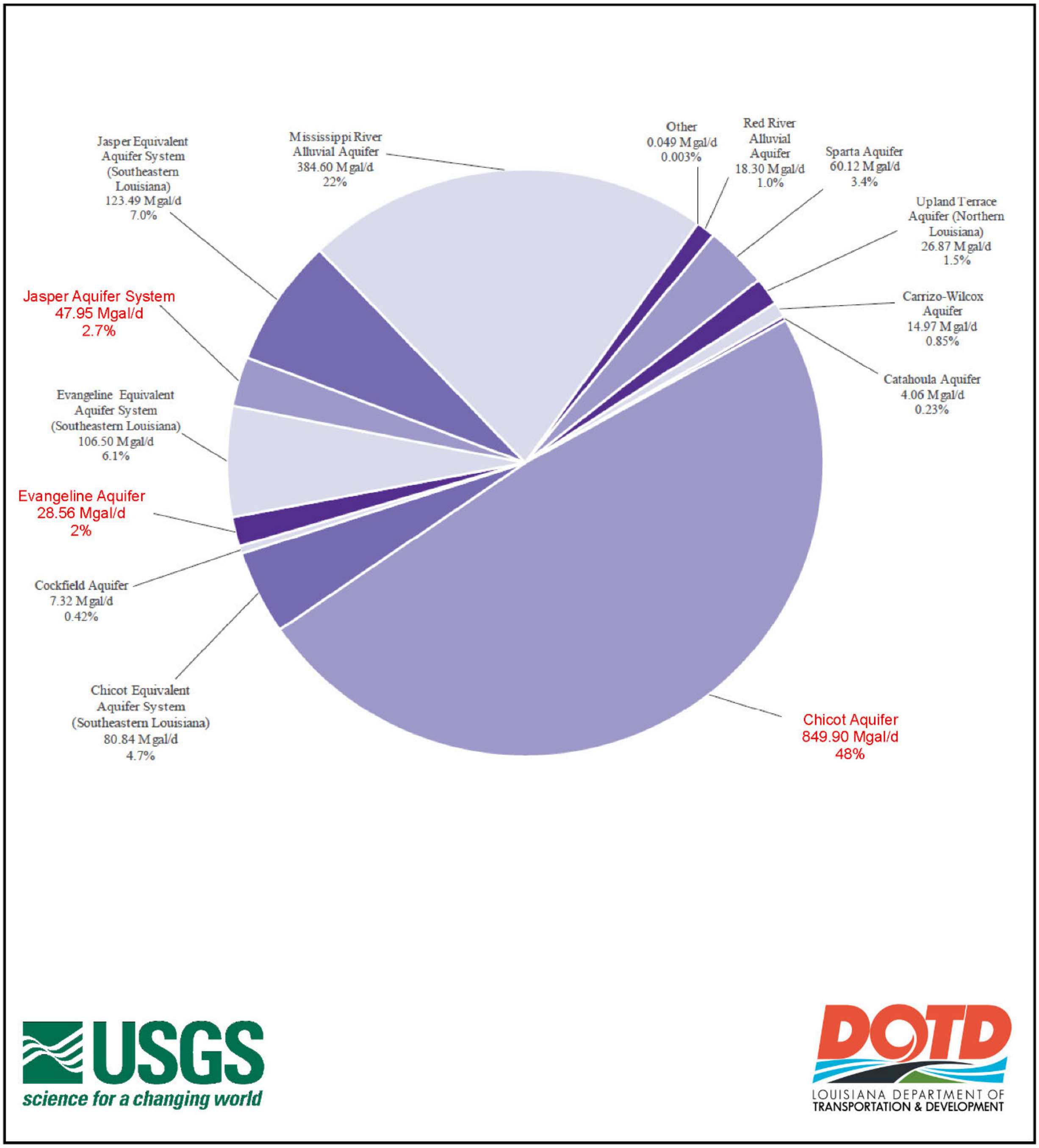

Figure 7.1 Groundwater withdrawals in Louisiana by aquifer system, 2015 (from Water Use in Louisiana, 2015, Water Resources Report No. 18)

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Overall, regional groundwater withdrawals within the Chicot aquifer have declined since 1985. Since the water levels are stabilized, withdrawal from the aquifers is not expected to have an effect on either the safety of the injection site (non-endangerment of USDWs) or injection operations. The target Frio Injection Interval at Project Minerva is separated by over 4,000 feet of geologic section (>1,100 feet net impermeable shale) from the shallow USDWs (<10,000 mg/L TDS) (Figure 7.1). Multiple additional saline "buffer aquifers" also exist between the top of the confining zone and base of the lowermost USDW, mitigating the vertical transmission of fluids upwards. Regional aquifer data on the characteristic for the systems is contained in the in the table below (from Wesselmann and Arrow, 1971) for the aquifers in the Beaumont and Orange, Texas. These data are regional and applicable across the Sabine River into southwestern Louisiana.

Aquifer	Transmissivity (gpd)	Storativity	Permeability (cm/sec)
Chicot Aquifer Upper Unit	19,500	4.5×10^{-4}	3.1×10^{-4}
Chicot Aquifer Lower Unit	69,200	1.5×10^{-3}	2.5×10^{-2}
Evangeline Aquifer	34,000	3.0×10^{-5}	1.4×10^{-2}

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8 Regional Groundwater Flow

Groundwater moves through aquifer systems from areas of high hydraulic head to areas of lower hydraulic head. Regional uses from industry and the public water systems have some impacts on diverting the direction of flow.

The Chicot regional flow is in the direction of development. Major development of groundwater occurs around the Lake Charles area. In Cameron Parish, due to aquifer development, the direction of groundwater flow is primarily north and northeast (Lovelace et al, 2004).

A map of the potentiometric surface for the Chicot aquifer (Figure 8.1) shows the direction of groundwater flow. Lovelace et al. (2004) indicated that the flow direction is towards major pumping areas such as Lake Charles in Calcasieu Parish and the northern part of Acadia Parish and south Evangeline Parish, where there is heavy pumping for industrial and irrigation uses. Control points and wells in the analysis are located on Figure 8.1. The direction of flow of groundwater is downgradient at 90 degrees to the potentiometric contours at right angles. An additional issue from pumping and heavy groundwater usage is the upwards coning of saltwater that can occur as response to freshwater withdrawal. The result is higher salinity waters being pulled upwards as pumping increases in aquifers that are hydraulically connected. Along the coast in the southwestern and southern portion of Louisiana, saltwater is being slowly pulled inland (northwards) due to over pumping of groundwater aquifers for industry and agriculture, especially during the peak rice irrigation and aquaculture harvesting seasons. Two regional cross sections (Figure 8.2) extending across Calcasieu Parish show that the southern portion of the parish is impacted by saltwater encroachment in the Chicot aquifer (and by default the Evangeline) from the Gulf of Mexico. Increasing chloride concentrations between 1968 and 1984 indicated that a northwards or upward movement of the freshwater-saltwater interface in areas east and south of Lake Charles.

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